

**High proper motion objects towards the inner Milky Way:
characterisation of newly identified nearby stars from the VISTA
Variables in the Vía Láctea Survey**

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ABSTRACT

The census of the Solar neighbourhood is still incomplete, as demonstrated by recent discoveries of many objects within 5–10 pc from the Sun. The area around the mid-plane and bulge of the Milky Way presents the most difficulties in searches for such nearby objects, and is therefore deficient in the known population. This is largely due to high stellar densities encountered. Spectroscopic, photometric and kinematic characterization of these objects allows better understand the local mass function, the binary fraction, and provides new interesting targets for more detailed studies. We report the spectroscopic follow-up and characterisation of 12 bright high PM objects, identified from

the VISTA Variables in Vía Láctea survey (VVV). We used the 1.9-m telescope of the South African Astronomical Observatory (SAAO) for low-resolution optical spectroscopy and spectral classification, and the MPG/ESP 2.2m telescope Fiber-fed Extended Range Optical Spectrograph (FEROS) high-resolution optical spectroscopy to obtain the radial and space velocities for three of them. Six of our objects have co-moving companions. We derived optical spectral types and photometric distances, and classified all of them as K and M dwarfs within 27 – 264 pc of the Sun. Finally, we found that one of the sources, VVV J141421.23-602326.1 (a co-moving companion of VVV J141420.55-602337.1), appears to be a rare massive white dwarf that maybe close to the ZZ Ceti instability strip. Many of the objects in our list are interesting targets for exoplanet searches.

Key words: *proper motions – stars: low-mass – (stars:) white dwarfs – (stars:) binaries: visual – (Galaxy:) solar neighbourhood – techniques: spectroscopic.*

1. Introduction

M-dwarfs account for over 70% of stellar systems in the solar vicinity (Henry *et al.* 1997). Most of them are single (~ 60 -70%; Fischer & Marcy 1992; Bergfors *et al.* 2010), making them more likely to host (potentially habitable) planets (e.g. Kraus *et al.* 2012). For comparison, the single star fraction is $\sim 54\%$ for solar-type stars (Duquennoy & Marcy 1991; Raghavan *et al.* 2010) and it is $\sim 0\%$ for massive stars (Preibisch *et al.* 1999). This makes M-type dwarf stars the most numerous potential planet hosts of all the stellar classes (Lada 2006). Furthermore, all exoplanet detection methods (radial velocity, transits, direct imaging with Adaptive Optics and astrometry) are more sensitive to planets with host stars of lower masses. A number of exoplanet search programs are aggressively targeting M-dwarfs with radial velocities (e.g. M2K; Apps *et al.* 2010) and with transits (RoPACS and MEarth; Irwin *et al.* 2014). The first exoplanet to be imaged was orbiting a brown dwarf (BD) at ~ 70 pc (Chauvin *et al.* 2005), and there is a on-going debate for an astrometrically discovered third planetary mass body in a nearby BD pair at ~ 2.3 pc (Boffin *et al.* 2014; Sahlmann & Lazorenko 2015).

One of the most powerful methods to identify nearby stars is through identifying proper motion (PM), and by exploiting a PM search at infrared wavelengths, offers an additional advantage: cool objects are intrinsically brighter at those wavelengths than in the optical because their spectral energy distributions peak at $\lambda > 1 \mu\text{m}$ (Lépine & Gaidos 2011) published an all-sky catalog of M-dwarfs with apparent near-Infrared (near-IR) magnitude $J < 10$. They selected 8889 stars from the on-going SUPERBLINK (e.g. Lépine & Shara 2005) survey of stars with $\mu > 40 \text{ mas yr}^{-1}$, supplemented at the bright end with the TYCHO-2 catalogue. Recently, Lépine *et al.* (2013) presented a spectroscopic catalog of the 1564 brightest ($J < 9$) M-dwarf candidates in the northern sky.

The majority of surveys avoid Galactic plane and bulge, or are substantially incomplete near to these regions. However, these regions offer considerable latent potential for new discoveries of nearby low-mass stars and brown dwarfs. This is especially true for nearby or bright examples that have been overlooked in previous searches due to confusion caused by high stellar densities and background contami-

nant objects (Folkes *et al.* 2012; Luhman 2013; Scholz 2014). A fortuitous aspect of discoveries at low Galactic latitudes is that these regions typically offer many suitable reference stars for high-Strehl ratio AO follow-up observations.

This is the third paper of a project, after Beamín *et al.* (2013) and Ivanov *et al.* (2013), to generate a uniform catalog of high-PM objects within the VVV footprint, and characterise them with spectroscopic follow-up observations. It is organised as follows: the next section describes the sample selection, and the new observations. Section 3 describes the spectral type estimation, the distance measurements, and reports on the co-moving companions. Finally, in section 4 we present summary and conclusions.

2. Sample selection and observations

The targets reported here were identified during a test phase of our method to search for high PM objects using the VVV survey database. The VVV observations at the time of the search covered the period from Feb 2010 to Mar 2013. Our PM analysis techniques makes use of four K_S -band epochs, preferentially selected with equally spaced epochs, obtained under similar seeing and photometric conditions. We used the source catalogs generated by the Cambridge Astronomical Survey Unit (CASU)¹. Their astrometric precision is 0.05–0.09 arcsec. Pairs of catalogs for neighbouring epochs were cross-identified with a matching radii scaled to correspond to a maximum PM of 5 arcsec yr^{−1} using the STILTS code (Taylor 2006). This procedure was repeated for all sequential pairs of epochs, yielding three PM measurements for each object. Next, we removed candidates with inconsistent PMs. At this stage of the project we were interested in nearby objects with larger apparent motions, so we imposed two additional constraints selecting only brightest stars with $K_S < 13.5$ mag, and with PMs exceeding 3 times the astrometric errors. All final candidates were visually inspected. The proper motions of targets were estimated using the 2MASS and last available VVV epoch data, that gave a typical error of proper motion equal to 0.01 arcsec yr^{−1}. The resulting catalog and a more detailed description of the search will be reported in Kurtev *et al.* (2016).

For this paper we selected 12 high-PM stars based on their magnitudes and the visibility at the moment of the observations. Four of our targets have been previously identified as high PM stars: VVV J121051.57-642528.5 and VVV J164622.06-420118.8 were listed in TYCHO-2 catalog (Høg *et al.* 2000) as TYC 8982-1530-1 and TYC 7875-141-1, respectively. VVV J122701.70-634203.7 and VVV J141420.55-602337.1 were reported by (Finch *et al.* 2010) as 2MASS J122701.32-634203.1 and 2MASS J141420.90-602336.1, respectively.

Throughout this paper we adopt a naming convention with the survey abbreviation followed by the J2000 coordinates: VVV JHHMMSS.ss-DDMMSS.s, according to the IAU convention.

¹<http://casu.ast.cam.ac.uk/surveys-projects/vista>

2.1. Radcliffe/SAAO spectra

Low-resolution spectra of 12 stars were acquired on 2013 Apr 4–7 using the Grating Spectrograph with the SITE (Scientific Imaging Technologies, INC.) CCD mounted on the 1.9-m Radcliffe telescope at the South African Astronomical Observatory (SAAO), Sutherland. We made use of grating no. 7 with $300 \text{ lines mm}^{-1}$ and a slit with a projected width of 1.35 arcsec . During observations seeing varied from 0.8 to 2.5 arcsec , with an average around 1.5 arcsec . The total duration of an exposure was $600\text{--}1200 \text{ s}$, depending on object's brightness, split into two individual integrations. Usually, two or three standards were observed on each night, selected among the list: LTT 3864, LTT 4816, LTT 7379, LTT 6248, and CD-32° 9927. This allowed us to flux-calibrate the low-resolution spectra in absolute units. The wavelength calibration was performed using CuAr reference lamp spectra. All the data reductions and calibrations were carried out with standard IRAF² procedures. The final spectra from the first two nights cover the range $4292\text{--}8289 \text{ \AA}$ and from the last two nights $3761\text{--}7735 \text{ \AA}$ with a resolving power of $R \sim 1000$.

2.2. FEROS/ESO spectra

We obtained radial velocities (RV) for VVV J121436.36-640808.4, VVV J132355.14-620324.9 and VVV J164810.92-414014.9 with the Fiber-fed Extended Range Optical Spectrograph (FEROS; Kaufer *et al.* 1999), at the MPG/ESP 2.2m telescope. The instrument has a resolving power of $48\,000$ over the spectral range $350\text{--}920 \text{ nm}$. FEROS uses two fibers of 2 arcsec , in diameter with a separation of 2.9 arcmin . One of the fibers was placed on the star and the other was fed by a Thorium-Argon lamp to obtain a better wavelength calibration (Object-calibration mode). The observations were carried out on the nights 15 and 16 Feb 2015. The seeing conditions for each night were varied between $0.5\text{--}1.1 \text{ arcsec}$ and $0.6\text{--}1.4 \text{ arcsec}$, respectively.

In order to reduce the data we obtained the standard calibration frame for this instrument (i.e. bias, flat, lamps). Here we give a brief summary of the reduction process, but the reader is referred to Jordán *et al.* (2014) and Brahm, Jordán and Espinoza (2016) for a detailed explanation of each step. First, the bias was removed, and the flat fielding correction was applied. Next, one-dimensional spectra were optimally extracted for each echelle order of both the science and the calibration spectra. The wavelength calibration is first processed order by order using a reference Thorium-Argon lamp, each order is fitted against this reference until the R.M.S. is less than 70 m s^{-1} then a global solution is performed iteratively until an R.M.S. below 100 m s^{-1} is reached. Then, the solution is applied to the target spectrum. Finally, a barycentric correction is applied using the Jet Propulsion Lab

²IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

ephemerides (JPLEphem) package³.

The reduced spectra are cross correlated with a set of synthetic spectra from Coelho *et al.* (2005) to estimate the physical parameters in an iterative way, and after convergence a binary mask is used to measure the RV via the cross correlation function (Baranne *et al.* 1996). A simple Gaussian is fitted to the cross correlation function with the binary mask, and the mean is taken as the RV of the star. The binary masks are the same ones used by the HARPS data reduction (Mayor *et al.* 2003).

2.3. VISTA Variables in Vía Láctea survey

VISTA Variables in the Vía Láctea (VVV) is a public ESO (European Southern Observatory) near-infrared (near-IR) survey that is mapping the Milky Way Bulge and an adjacent section of the mid-plane with the VISTA telescope (Minniti *et al.* 2010).

The VISTA is a 4.1-m telescope, located on Cerro Paranal, equipped with VIR-CAM (VISTA InfraRed CAMera; Dalton *et al.* 2006), a wide-field camera producing $\sim 1 \times 1.5 \text{ deg}^2$ tiles, working in the 0.9–2.4 μm wavelength range. The VISTA data are processed with the VISTA Data Flow System (VDFS; Irwin *et al.* 2004; Emerson *et al.* 2004) pipeline at the Cambridge Astronomical Survey Unit. The data products are available through the ESO archive or the specialised VISTA Science Archive (VSA; Cross *et al.* 2012).

The VVV survey covers a total area of 562 deg^2 in the Galactic bulge and southern disk. The VVV database now contains multicolour photometry in $ZYJHK_S$ bands, and multiple epochs in the K_S -band, monitoring a billion sources in total (Saito *et al.* 2012). The time baseline already exceeds 5 years, from the first observations acquired in Oct 2009, and the plan is to extend this for a couple more years until the survey is completed. The VVV survey gives unique information on these inner regions of the Milky Way that have remained mostly uncharted due to crowding and heavy extinction, allowing a number of studies of stellar populations and Galactic structure (*e.g.* Hempel *et al.* 2014). In particular, the time baseline, combined with the astrometric accuracy of $\sim 25 \text{ mas}$ for a $K_S = 15.0 \text{ mag}$ source and $\sim 175 \text{ mas}$ for $K_S = 18.0 \text{ mag}$ enable a number of interesting astrometric studies. The typical proper motion measurements for non saturated and approximately bright sources for the first four years reach an accuracy of $\sim 10 \text{ mas yr}^{-1}$ ($K_S = 15.0 \text{ mag}$) and $\sim 20 \text{ mas yr}^{-1}$ ($K_S = 18.0 \text{ mag}$). More details of astrometry with the VVV are given in Saito *et al.* (2012). We have just started to exploit the VVV database for proper motion studies: Beamín *et al.* (2013) reported the first VVV brown dwarf discovery, Ivanov *et al.* (2013) found seven new companions to known high PM nearby stars, Libralato *et al.* (2015) produced a high-precision astrometry reduction pipeline for the VVV survey data, and Kurtev *et al.* (2016) produced a catalogue of 3 003 high proper motion stars in the VVV fields.

³<https://pypi.python.org/pypi/jplephem>

2.4. Other photometric data

We complemented the VVV observations with archival multi-wavelength photometry to obtain their spectral energy distributions. Photometric data for our objects were found in the TYCHO-2 catalog Høg *et al.* (2000), the Fourth U.S. Naval Observatory CCD Astrograph Catalogue (UCAC4; Zacharias *et al.* 2012, 2013), the Deep Near-Infrared Survey of the Southern Sky (DENIS; Epchtein *et al.* 1997), the Two Micron All Sky Survey (2MASS; Skrutskie *et al.* 2006), the Wide-Field Infrared Survey Explorer (AllWISE; Wright *et al.* 2010; Cutri *et al.* 2013) and Spitzer Galactic Legacy Infrared Mid-Plane Surveys Extraordinaire (GLIMPSE; Benjamin *et al.* 2003). The cross-identification of the catalogs was carried out with Topcat (Taylor 2006), and we ensured that our high PM objects are correctly cross-identified with a visual inspection of the images, facilitated with the Aladin tool (Bonnarel *et al.* 2000). The photometric measurements are available in the online materials.

3. Results

3.1. Spectro-photometric characterisation

We derived spectral type for our targets using three methods: direct comparison with spectral templates, spectral indices, and spectral energy distributions (SEDs) fitting. We find good agreement between spectral types determined with the first two methods. The third method yields results, that sometimes differ by up to five sub-types. We attribute the poor agreement to the significant background contamination of the archival photometry – both for old photographic surveys, and the mid-infrared WISE and Neo-WISE surveys. We adopted as our final spectral types those obtained by the templates comparison, as the most direct and robust and adopt uncertainties of their estimation equal one sub-type.

3.1.1 Spectral typing by comparison with spectral templates

Nine of the twelve spectra showed the characteristics molecular absorption bands of K and M type stars (TiO, CaH), and they were compared to the primary K7V-M5V standards from Kirkpatrick *et al.* (1991, 1999) available from the Dwarf Archives⁴.

The template spectra were smoothed to the resolution of our data, normalised at 7500 Å, and a χ^2 minimisation over $\lambda=5000\text{--}8000$ Å was used to find the best match. The results are shown in Fig. 1. The types of some targets were adjusted by up to 0.5 sub-type after a visual inspection. The remaining three spectra indicated hotter stars, and for those earlier than K7 type objects we used the standards of Pickles (1998), following the same minimisation routine as before, but now over $\lambda=3800\text{--}8000$ Å. In case of VVV J121051.57-642528.5, we cannot find

⁴<http://www.dwarfarchives.org>

a convenient fit to the low resolution spectrum (see Fig. 1). Target was overexpose and detector worked in nonlinear regime, what prevented proper flux calibration. Spectral type of this object was estimated by comparison of Na I doublet around 5890 \AA in the high resolution spectrum with template spectrum. Both spectra were normalised by continuum. Fe I lines around Na I doublet fit perfectly what suggest similar rotation velocity. The derived spectral types are listed in Table 2.

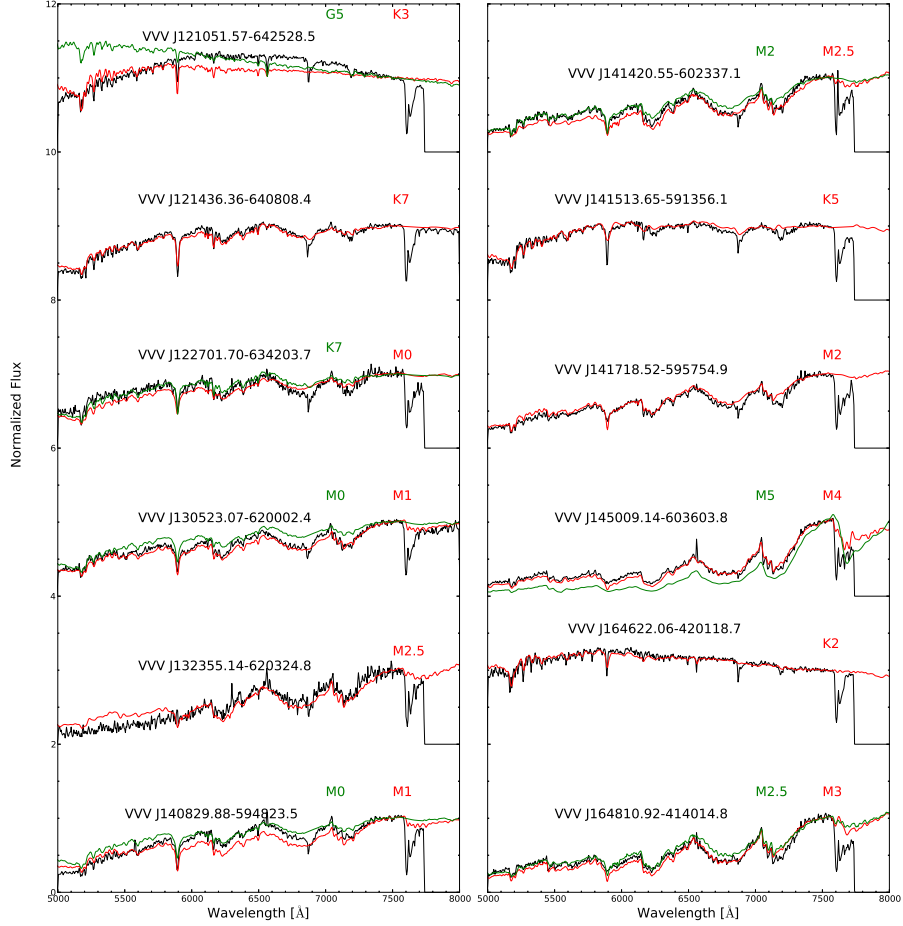


Fig. 1. Observed spectra (black lines) overplotted with the best fitted template spectra (red lines) and alternative comparison template spectra (green lines). The template spectra were taken from Kirkpatrick *et al.* (1991) and Pickles (1998) for objects with spectral types later, and earlier than K5, respectively. The absorption feature at $\sim 7600\text{--}7700 \text{ \AA}$ has telluric origin.

3.1.2 Spectral typing using spectral indices

Kirkpatrick *et al.* (1991) developed a system of spectroscopic indices for mid-K to late-M stars, and calibrated them versus the spectral types. Other index systems have been developed afterwards, but we prefer this one because it has been applied

to a large number of stars, providing broad comparison with literature data. We followed the definitions in their Table 6, but measured only three diagnostic index ratios, because of our narrower spectral coverage. We compared the results with their Fig. 6 to assign spectral types to the individual objects (Table 1). Our errors are tentative, derived from the intrinsic spread of the “calibrators” in Fig. 6 of Kirkpatrick *et al.* (1991). Our formal Poisson errors are negligible, and we also verified that a small velocity offset of $\pm 20 \text{ km s}^{-1}$ led to changes in the ratios of $\leq 0.5\%$.

For most stars the spectral types derived from different ratios agree well, with a exception VVV J140829.88-594823.5. To verify our classification we measured some K and M type spectra from the Dwarf Archives (Kirkpatrick *et al.* 1999), and successfully recovered the spectral classes of the test stars, typically with an uncertainty of 0.5-1 sub-types. However, ratio A appears to be the most reliable, because of the steeper calibration and wider dynamical range than the other ratios.

Table 1

Spectroscopic index ratios (as defined by Kirkpatrick *et al.* 1999), and derived spectral types.

Name (1)	Ratio A (2)	Sp. T. (3)	Ratio B (4)	Sp. T. (5)	Ratio C (6)	Sp. T. (7)
VVV J121051.57–642528.5	0.985	<K8	1.034	\leq K9		
VVV J121436.36–640808.4	1.081	M0.5 \pm 1.0	1.031	\leq M2	1.133	\leq M3
VVV J122701.70–634203.7	1.109	M0.5 \pm 1.0	0.957	<K8		
VVV J130523.07–620002.4	1.103	M0.5 \pm 1.0	1.042	\leq M2	1.163	\leq M4
VVV J132355.14–620324.9	1.125	M1.0 \pm 1.0	0.924	<K8	1.101	\leq M2
VVV J140829.88–594823.5	1.124	M1.0 \pm 1.0	1.075	M4.0 \pm 2.0	1.095	\leq M2
VVV J141420.55–602337.1	1.203	M2.5 \pm 0.5	1.050	\leq M3		
VVV J141513.65–591356.1	1.034	\leq K9	1.044	\leq M3		
VVV J141718.52–595755.0	1.120	M1.0 \pm 1.0	1.032	\leq M2		
VVV J145009.14–603603.9	1.345	M4.5 \pm 1.0	1.081	M4.5 \pm 2.0		
VVV J164622.06–420118.8	1.002	<K8	1.005	\leq K9	1.091	\leq M2
VVV J164810.92–414014.9	1.220	M2.5 \pm 0.5	1.064	M2.5 \pm 2.0		

3.1.3 SED fitting

To produce the spectral energy distribution (SED) and compare to stellar models we used the Virtual Observatory SED analyser (VOSA; Bayo *et al.* 2008), fitting the BT-settl 2012 models (Allard *et al.* 2012) and Kurucz ODFNEW/NOVER models (Castelli *et al.* 1997) to the data, first with a Bayesian approach, and then constraining the model parameters with a χ^2 minimisation over three parameter space: effective temperature T_{eff} , surface gravity $\log g$, and metallicity [Fe/H]. Increasing the number of photometric measurements and widening the wavelength coverage makes the fit more robust and reliable. Usually, the T_{eff} is the most stringently

constrained parameter, with uncertainties of order of ~ 200 K; The other parameters surface gravity and iron abundance, are usually, $\log g \geq 4.5$, and $[\text{Fe}/\text{H}] \geq -1$, with a typical scatter of 0.5 dex for both. The photometry used in the SED fitting is described in Sec. 2.4 and it is available in online materials.

Table 2

Spectral classifications (based on template comparison) and effective temperatures defined based on photometric spectral energy distribution, J -band magnitudes, proper motions (estimated based on 2MASS and the last available epoch of the VVV survey), spectro-photometric distances, and tangential velocities for the observed targets.

Name	Sp. T.	SED T_{eff} [K]	$J_{2\text{MASS}}$ [mag]	$\mu_{\alpha} \cos \delta$ [mas yr $^{-1}$]	μ_{δ} [mas yr $^{-1}$]	Dist. [pc]	V_{tan} [km s $^{-1}$]
VVV J121051.57-642528.5	K2	5300	8.211	-118 \pm 10	-47 \pm 10	55	33 \pm 7
VVV J121436.36-640808.4	K7	3900	9.424	-181 \pm 9	-46 \pm 9	55	49 \pm 10
VVV J122701.70-634203.7	K7	3700	12.742	178 \pm 10	-35 \pm 10	264	227 \pm 45
VVV J130523.07-620002.4	M1	3700	11.851	-169 \pm 8	-49 \pm 8	116	97 \pm 19
VVV J132355.14-620324.9	M2.5	3600	9.865	227 \pm 9	-200 \pm 9	35	50 \pm 10
VVV J140829.88-594823.5	M0	3600	10.340	-162 \pm 11	-32 \pm 11	68	53 \pm 11
VVV J141420.55-602337.1	M2.5	3700	11.739	-185 \pm 10	-65 \pm 10	84	78 \pm 16
VVV J141513.65-591356.1	K5	4000	10.974	-120 \pm 8	-143 \pm 8	144	127 \pm 25
VVV J141718.52-595755.0	M2	4000	11.113	-133 \pm 8	-95 \pm 8	69	53 \pm 11
VVV J145009.14-603603.9	M4	3000	10.533	-128 \pm 8	-130 \pm 8	27	23 \pm 5
VVV J164622.06-420118.8	K2	4700	9.963	-46 \pm 9	-60 \pm 9	117	41 \pm 8
VVV J164810.92-414014.9	M3	3200	10.807	-138 \pm 8	-263 \pm 8	48	68 \pm 14

3.2. Distance estimation

We were not able to measure parallaxes from the multi-epoch K_S -band VVV data as achieved by Beamín *et al.* (2013, 2015) and Smith *et al.* (2015). This is due to our targets being saturated on the VVV K_S images. Instead, we estimated their spectro-photometric distances from the spectral types we obtain (see Sec. 3.1), and from the 2MASS J and K_S photometry using the absolute magnitudes M_J , M_{K_S} from Pecaut & Mamajek (2013)⁵. For each object we calculated the distances for the two 2MASS photometric bands separately. Our final estimate was the average of these two measurements. The mean difference is $1.6\% \pm 0.8\%$, with a maximum value of 3.1% for object VVV J141513.65-591356.1. The affect of the sub-type classification uncertainty on the distance estimation is of the order of 15%, on average. The photometric uncertainties introduce uncertainties within 1–3% in the magnitude range we examine. Finally, our estimated spectro-photometric distances should have an associated error of $\sim 20\%$. Derived distances are listed in Table 2.

⁵http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

3.3. Co-moving wide binaries

Six of our objects have co-moving companions. We estimated the T_{eff} of the companions with SED fitting (see Sec. 3.1.3; the photometry is available in online materials). We also derived spectral types of companions using magnitude difference with the primary in J band and the absolute magnitudes for a given spectral type from Pecaut & Mamajek (2013). The basic information about the binary systems are summarised in Table 3.

Table 3

Binary systems investigated in this paper. The columns are: spectral types from this work, T_{eff} defined based on photometric spectral energy distribution, 2MASS J -band magnitudes, angular separations in arcsec, photometric distances in pc, and proper motions in celestial coordinates.

Name	Sp. T.	SED T_{eff} [K]	$J_{2\text{MASS}}$ [mag]	ρ ["]	Dist. [pc]	ρ_p [a.u.]	$\mu_\alpha \cos \delta$ [mas yr ⁻¹]	μ_δ [mas yr ⁻¹]
VVV J121051.57-642528.5	K2	5300	8.211	45.8	55	2521	-118±10	-47±10
VVV J121050.12-642443.5	M5 ^a	3100	13.064	-	-	-	-108±10	-49±10
VVV J121436.36-640808.4	K7	3900	9.424	21.3	55	1170	-181±9	-46±9
VVV J121433.35-640801.0	M4 ^a	3100	12.234	-	-	-	-176±9	-52±9
VVV J140829.88-594823.5	M0	3600	10.340	16.7	68	1135	-162±11	-32±11
VVV J140831.63-594834.3	K8 ^a	3600	10.024	-	-	-	-155±11	-31±11
VVV J141420.55-602337.1	M2.5	3700	11.739	11.7	84	983	-185±10	-65±10
VVV J141421.23-602326.1	-	-	16.752	-	-	-	-171±10	-78±10
VVV J141718.52-595755.0	M2	4000	11.113	2.8	69	193	-133±8	-95±8
VVV J141718.30-595756.0	M3 ^a	-	11.845 ^b	-	-	-	-143±8	-105±8
VVV J164622.06-420118.8	K2	4700	9.963	5.0	117	585	-46±9	-60±9
VVV J164621.64-420119.0	M0 ^a	4300	11.520	-	-	-	-40±9	-61±9

^a Sp. types of companions estimated base on magnitude differences and absolute magnitudes given by Pecaut & Mamajek (2013). ^b System not resolved in achival images, magnitudes were taken from VVV catalogs and then transform to the 2MASS system.

3.4. A possible massive white dwarf near the ZZ Ceti instability strip

Finch *et al.* (2010) reported that the object UPM 1414 – 6023A (=VVV J141420.55 – 602337.1) has a common PM companion UPM 1414 – 6023B (=VVV J141421.23 – 602326.1).

This object is too faint and it is not detected by 2MASS, but it is relatively bright on the optical SuperCOSMOS plate, suggesting that may be a white dwarf. We do not have a spectrum of this star. We compiled a set of colours, including the VVV $ZYJHK_s$ magnitudes (transforming the JHK_s to the 2MASS system follow-

ing Soto *et al.* 2013), and the DENIS *I*-band, and compare them with the synthetic colour of pure hydrogen white dwarfs from Pierre Bergeron webpage⁶ (Holberg & Bergeron 2006; Kowalski & Saumon 2006; Tremblay *et al.* 2011; Bergeron *et al.* 2011).

The positions of VVV J141421.23 – 602326.1 on the colour-colour and colour-magnitude diagrams indicate effective temperature $T_{\text{eff}} \sim 12\,000$ K and a relatively high mass of $\sim 1 M_{\odot}$ (Fig. 2). These parameters place it in the ZZ Ceti instability strip. Typically, the ZZ Ceti pulsators have $\log g \sim 8.2$ (see Fig. 33 in Gianninas *et al.* 2011), that corresponds to mass $\sim 0.6 M_{\odot}$ so, VVV J141421.23 – 602326.1 is unusually massive for this class of variables. There are only around 30 known stars more massive than $0.8 M_{\odot}$ within the approved ZZ Cetis, and only three of them are more massive than $1 M_{\odot}$ (Castanheira & Kepler 2014). Each new member of this tiny family is valuable, because the larger number of massive pulsators will allow to probe the ensemble internal structure of the high-mass end of the ZZ Ceti instability strip.

Further spectroscopic and photometric follow-up is needed to confirm nature and to determine the age of this object. High time resolution photometry could detect its variability and if it is indeed a ZZ Ceti star, providing us with additional constraints about its structure and composition.

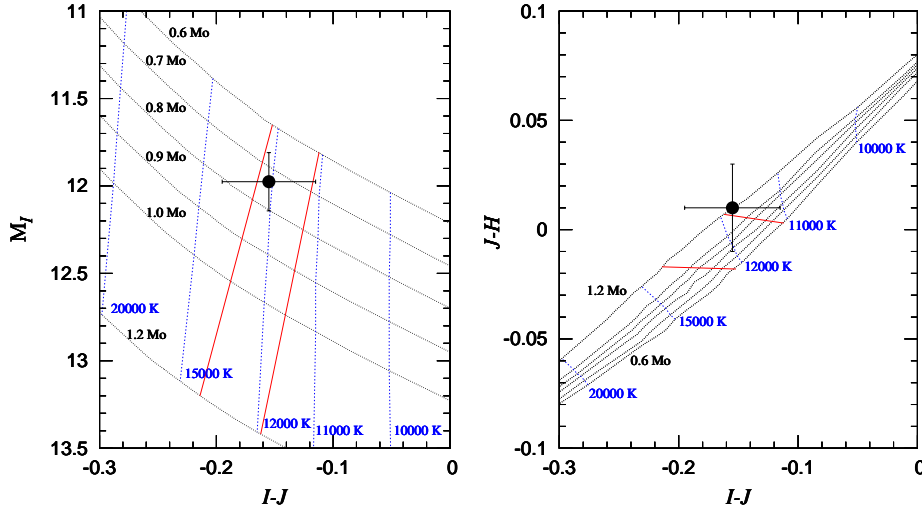


Fig. 2. Position of our new massive ZZ Ceti type pulsator candidate, VVV J141421.23-602326.1, in the colour-magnitude diagram (left panel) and colour-colour diagram (right panel). The black dot represents the measurements of VVV J141421.23-602326.1 along with the 3-sigma errorbars. The black dashed lines represent the synthetic colours for a given mass for a pure hydrogen atmosphere model. The blue dashed lines show the model isotherms. The red solid lines present borders of ZZ Ceti instability strip taken from Gianninas *et al.* (2011).

⁶<http://www.astro.umontreal.ca/~bergeron/CoolingModels>

3.5. Kinematics

We measured radial velocities for three objects: VVV J121436.36-640808.4, VVV J132355.14-620324.9 and VVV J164810.92-414014.9, using FEROS spectrograph at the MPG/ESP 2.2m telescope (Sec. 2.2). The UVW galactic space velocities were computed with GAL_UVW routine from the IDL Astronomy User's Library. The results are listed in Table 4. We used the BANYAN II web tool⁷ (Gagné *et al.* 2014; Malo *et al.* 2013) to estimate the probability that these three objects may be members of any known young moving group. Typically, the derived spatial velocities are consistent with old field population: 100, 99.61, and 36.47 %, for VVV J132355.14-620324.9, VVV J164810.92-414014.9, and VVV J121051.57-642528.5, respectively. There is a marginal possibility of 0.39 % that VVV J164810.92-414014.9 may belong to the young field. This possibility is considerable for VVV J121051.57-642528.5 - 33.60 %. Finally, there is 29.81 % probability that the last object may belong to the Argus moving group and marginal chance of 0.11 % that it may belong to β Pictoris moving group. Although, high resolution spectrum of this target does not show Li I doublet at $\sim 6708 \text{ \AA}$, what suggests that its age is higher than 150 Myr and excludes membership to any known young moving group.

Table 4

Radial velocities RV and UVW galactic space velocities. All velocities are expressed in km s^{-1} .

VVV Name	RV	U	V	W
J121051.57-642528.5	3.27 ± 0.01	-23.7 ± 3.0	-16.0 ± 1.6	-17.0 ± 2.0
J132355.14-620324.9	123.20 ± 0.03	100.4 ± 5.4	-79.0 ± 3.9	-36.4 ± 7.5
J164810.92-414014.9	-35.08 ± 0.09	-52.4 ± 3.6	-52.9 ± 11.9	-15.8 ± 2.7

4. Summary and conclusions

We obtained spectroscopic follow-up observations of twelve new high PM objects found by the VVV survey during the initial testing of our searching method, and we also looked for possible new wide binary companions. We derived their optical spectral types and photometric distances.

All of the analysed objects are K and M dwarfs located at 27–264 pc from the Sun and are bright enough for further follow-up and search of planets using state of the art and upcoming NIR instruments. Also, all objects are in the densest regions of the Milky Way, surrounded by a plethora of bright stars, very suitable for AO imaging. That makes our targets ideal for searches of close neighbours. From

⁷<http://www.astro.umontreal.ca/~gagne/banyanII.php>

the other side, the surrounded stars are ideal comparison stars for precise relative photometry, variability and transit studies.

VVV J141421.23-602326.1, a co-moving companion of VVV J141420.55-602337.1, is a candidate for being a rare massive ZZ Ceti type pulsator. Further spectroscopic and photometric follow-up is needed to better constrain nature and age of this object.

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